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Langmuir Probe Measurement Techniques and Data Analysis for LAPPS

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Langmuir Probe Measurement Techniques and Data Analysis for LAPPS

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Abstract

Langmuir probe diagnostics have been applied to an inductively coupled test discharge as part of the diagnostics development effort for the Large Area Plasma Processing System at NRL. The method of calculating electron energy from the EEDF derived from the probe second derivative is compared with more traditional methods of fitting the probe characteristic to a known function assuming a Maxwellian distribution. It is shown that under some circumstances the local plasma around the probe can be perturbed such that fewer electrons are sourced to the probe than theory would predict for a non-perturbing diagnostic, resulting in a higher average electron energy.

1 Introduction

In a previous paper [1], we presented data taken with a variety of diagnostics in the LAPPS plasma system at NRL. Langmuir probes are one of the primary tools utilized to analyze plasmas. Often results are presented that rely heavily on interpretation of Langmuir probe signals. However, there are many subtle problems encountered which make interpretation of probe data an experiment within itself. Physical contamination of the probe, resolution capabilities of the recording devices, and protection from radiofrequency (RF) fluctuations in plasma potential were all experimental problems to overcome. Even with the data successfully recorded, the method of analyzing the data could substantially effect the outcome. In this paper we give a more detailed description of the Langmuir probe diagnostic techniques referred to in the previous work.

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2 Experiment

The data was taken in a large unmagnetized inductively coupled plasma (ICP) source. An illustration of the source is shown in Figure 1. Power is coupled to the plasma through a 1/2" thick, 10" diameter Pyrex window using a 3-turn spiral antenna. This antenna is fed from an N-type coax cable attached to a 700W 13.56 MHz RF power supply through a Pi-configuration matching network. When the matching circuit is tuned, the reflected power measured is less than 2% of the total applied. The supply is run in pulsed operation with 200 ms pulses in a 10% duty cycle. The chamber is evacuated to a base pressure of better than 10^{-6} Torr with a cryopump. Argon, Oxygen, or Nitrogen is introduced into the chamber at 20 or 100 mTorr. A tungsten filament was fixed in the chamber to provide additional background ignition plasma when necessary. The typical plasma density with this device was $10^{10} - 10^{11} cm^{-3}$.

Two Langmuir probes were positioned such that the plasma could be scanned horizontally or vertically. Each probe has a 2 mm long 0.5 mm diam cylindrical carbon tip and is fitted with high impedance shielded inductors and a capacitively coupled secondary electrode to minimize distortion from RF potential variations [2]. Carbon was used as the probe material to reduce errors in probe area arising from material sputtering from the probe surface. The probe and circuit setup is shown in Figure 2. The probes are biased using a programmable power supply driven by a function generator. The probe current is obtained by measuring the differential voltage across resistor R using an isolation amplifier circuit. This voltage signal is input to a CAMAC 12-bit digitizer. Using LabView software, the characterstic can be averaged over an arbitrary number of plasma pulses to minimize noise signals. The probes were also periodically cleaned through electron bombardment during data taking by biasing them to high positive voltages with the discharge running.

3 Probe Data Analysis

There are many ways of analyzing probe data. For this work we have chosen two of the traditional methods which give an average electron energy. The simplest approach to interpreting the characteristic is to fit the ion collection portion of the characteristic to a linear or power function and the electron retardation region to an exponential function, i.e.,

$$I = a_0(V_p - V_B)^{a_1} + a_2 e^{(V_p - V_B)/T_e} \tag{1}$$

with V_p the plasma potential, V_B the probe bias voltage, and T_e the electron temperature. Typically $a_1 \approx 1/2$. A variation of this method is to fit an exponential over the first or second derivative of the probe characteristic, since this de-emphasizes the ion contribution, which presumably varies more slowly. These methods have the advantage being physically realistic and easily employed. Sometimes the fit can be quite good, as seen in Figure 3. The major drawback is that one assumes a Maxwellian distribution function, which may not be true, especially in processing plasmas.

For non-Maxwellian electron energy distribution functions (EEDF's), the probe data can be analyzed using the Druyvesteyn method [3], where the EEDF is related to the second derivative of the probe current as

$$F(e(V_p - V_B)) = \frac{4}{Ae^2}\sqrt{\frac{m(V_p - V_B)}{2e}}\frac{d^2 I}{dV_B^2} \tag{2}$$

where A is the probe area, V_p the plasma potential, and V_B the probe bias. Although this is more rigorous from a theoretical standpoint, this method has disadvantages experimentally. Small errors in the probe characteristic, such as noise, become greatly amplified when differentiated twice. This results in a curve representing an non-physical EEDF due to features that are artifacts of signal noise or probe contamination. It also requires high time resolution so that information is not lost due to lack of digital bandwidth. This results in the opposite problem, where details of the EEDF will be smoothed out.

The derivatives of the probe current can be arrived at with analog devices [4], which necessitates recording the derivatives at the same time as the data is taken. This involves another level of experimental complexity in that a wide bandwidth analog differentiator and noise filtering equipment are needed. With the widespread use of powerful personal computers, one can differentiate the probe characteristic digitally. In this paper we employ the sliding polynomial method of Savitsky-Golay [5]. A 2nd order polynomial was used as we found this to be better suited to filtering some of the noise. The window size to use in the fitting routine was a trial and error type procedure. An overly large window size generally resulted in a overly rounded distribution function and thus a higher average electron energy. Another digital filtering technique used was a Gaussian filter in frequency space, where the width of the Gaussian can be adjusted to remove digital noise. This has the advantage of requiring much less computation time and the ability to fine tune the filter quickly. Obviously, both of these digital techniques have a certain amount of subjectiveness at the hands of the operator making the computations, so it was essential to perform many comparisons over a range of data and fitting conditions.

4 Results

Figure 4 shows EEDF's calculated from Savitsky-Golay polynomial fitting over 100 points out of 2048 total with the probes positioned directly under the pyrex window in 20 mTorr each of nitrogen, argon and oxygen. In comparison, Figure 5 shows the EEDF's calculated at 100 mTorr pressure. One of the results that was puzzling was the apparent lack of low energy electrons in the argon curves. This seemed to be due to the plasma not being able to source enough electrons to the probe as the bias was turned up, although this was not seen in the other gases. The amount of perturbation was tested by changing the bias, and current drawn, from one of the probes while monitoring the current drawn from a second probe held at a fixed bias. For this test, a probe with ten times the normal surface area was used to draw the current in order to magnify the effect. The probes were placed 5 cm away from each other and the bias of the first probe was gradually increased to draw a larger amount of electron current. Figure 6 (a) shows the circuit setup for this test. At low power (75 W) and density ($10^9 cm^{-3}$) the perturbation of the plasma was quite evident as seen in Figure 6 (b), where the current of the second probe is visibly affected by the electron current drawn by the first probe. At higher powers the effect was not visible, but it was also impossible to draw the current corresponding to the previous bias without damaging the probe, so as extreme conditions could not be imposed. It is not unreasonable that some perturbation of the local plasma is responsible for the lack of electron current at low energies when the EEDF's were acquired at the higher densities of Figures 4 and 5. Why this is more evident in argon and not other gases will require more tests in a future work.

Table 1 shows the electron "temperature" calculated from the average electron energy obtained from the EEDF, compared with the temperature derived from fitting a portion of the characteristic to Equation 1, and also from approximating an exponential slope to the first derivative of the characteristic, as shown in Figure 3. The argon data has the most variance stemming from the disproportionately small representation of low energy electrons, and the less Maxwellian characteristics. The electron energies measured are otherwise somewhat typical for this type of discharge.

5 Summary

A 12-bit digital Langmuir probe data acquisition system for use in LAPPS has been set up and tested in a well studied plasma environment: an inductively coupled discharge. Possible perturbation to the plasma from the probes under some conditions may lead to a misrepresentation of the EEDF by depleting the low energy portion of the curve, particularly in argon. However, two different methods of fitting to a Maxwellian distribution were in agreement, and the error arising from this rounding is small. This is due to the fitting for such curves, specifically for the Langmuir type fit, being done primarily with small electron currents, or higher energy electrons. The contribution of the lower energy electrons is missed in this analysis, giving an overestimation of the electron temperature.

Acknowledgements

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Figure Captions

Figure 1: The inductively coupled plasma source used for probe calibration

Figure 2: (a) Illustration of double probe tip and (b) equivalent circuit setup. P1 and P2 represent the primary (collecting) and secondary (RF coupling) probes, Cx is a coupling capacitor with value much greater than the sheath capacitance, and Z1 and Z2 are shielded tuned RF filters.

Figure 3: (a) Curve fit of the electron retardation portion of the characteristic to equation 1 (b) Exponential fit to the first derivative.

Figure 4: EEDF's calculated for Argon, Nitrogen, and Oxygen at 20 mT.

Figure 5: EEDF's calculated for Argon, Nitrogen, and Oxygen at 100 mT.

Figure 6: The depletion of the electron saturation current of one probe by overbiasing the second probe in a low density, low power discharge ($10^9 cm^{-3}$, 75 W).

Table 1: Resulting effective temperatures for the plasmas tested using the three methods of analysis.

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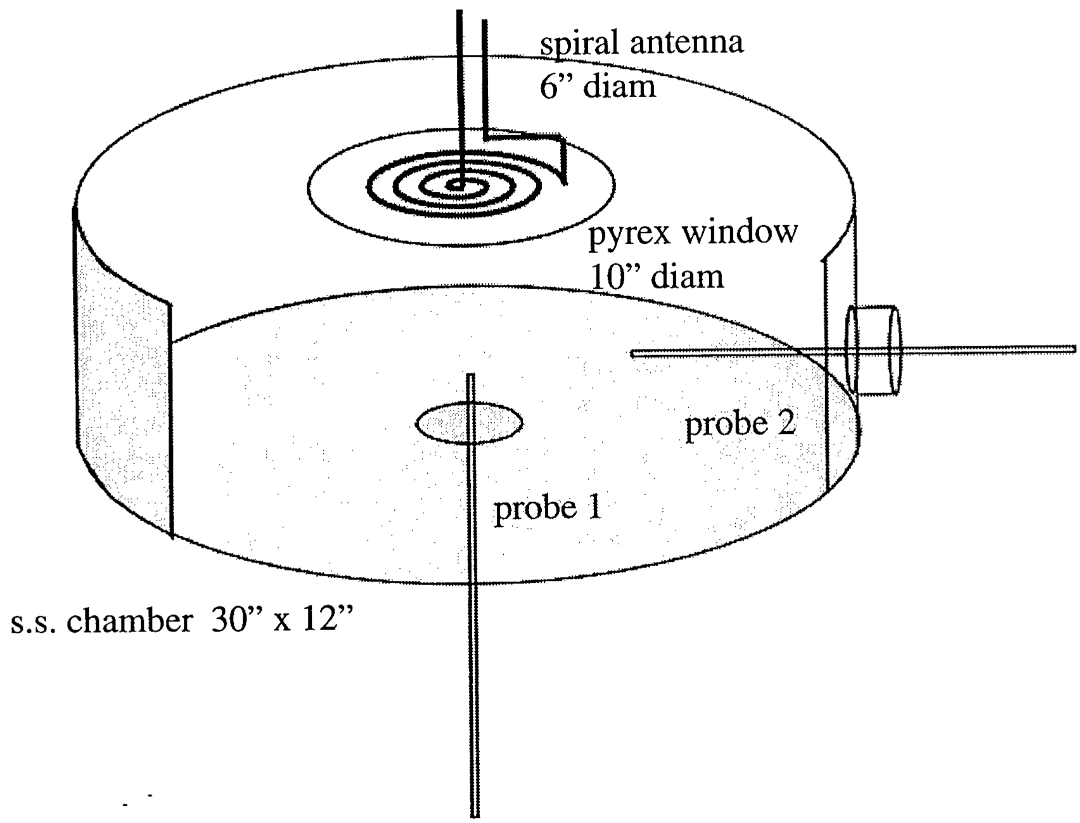
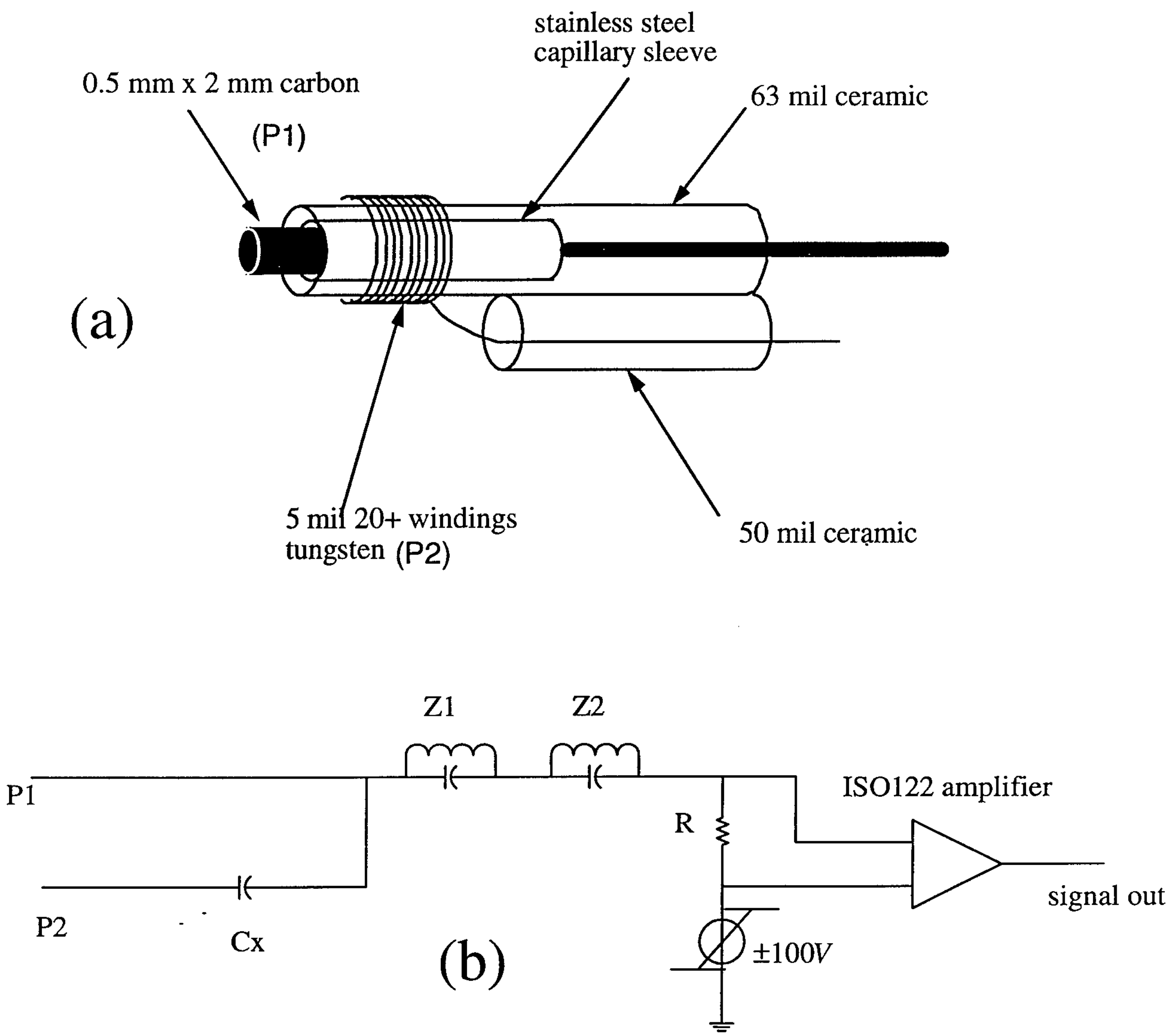

spiral antenna
6" diam
pyrex window
10" diam
probe 2
probe 1
s.s. chamber 30" x 12"

Figure 1

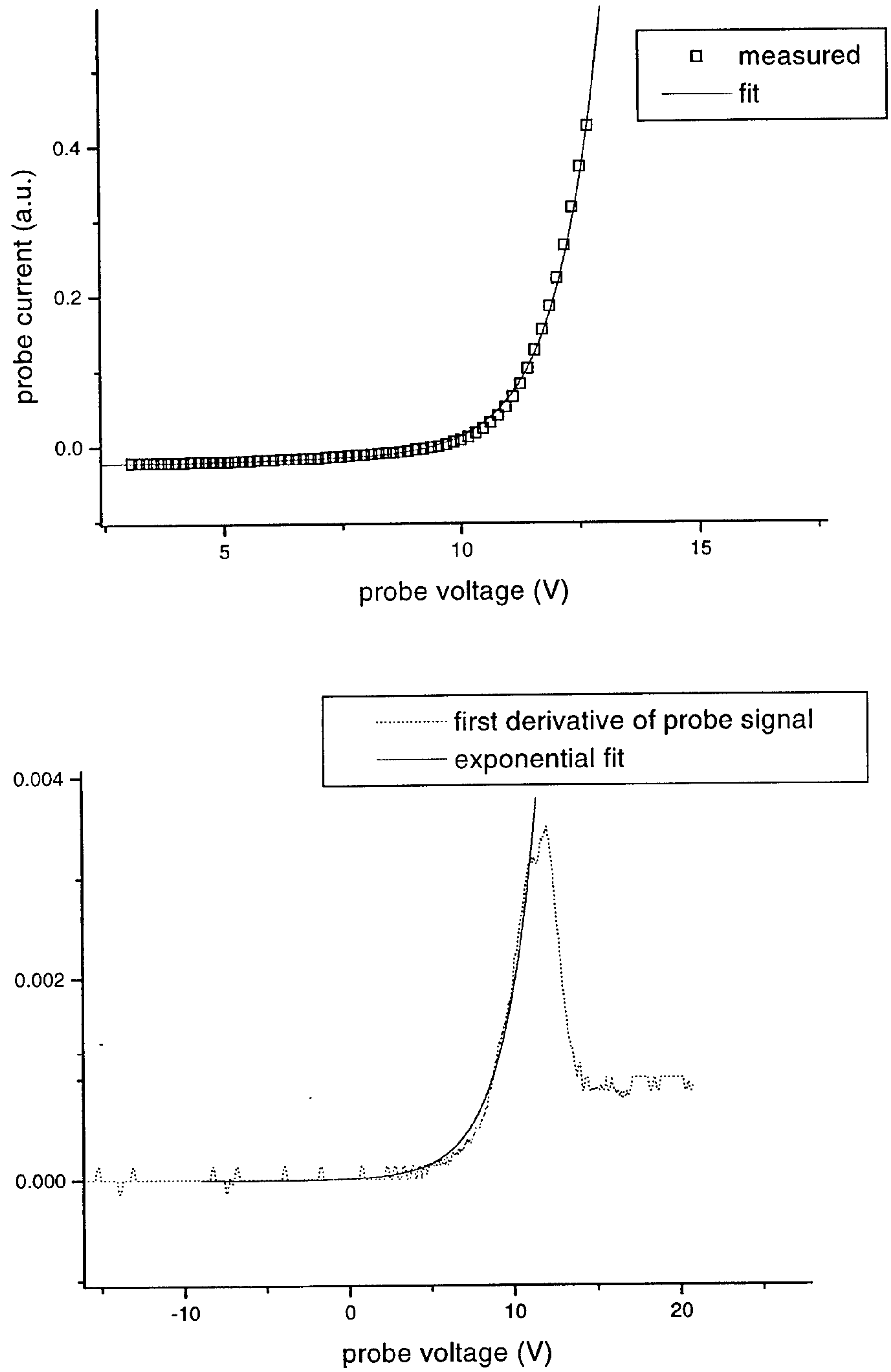


stainless steel
capillary sleeve
0.5 mm x 2 mm carbon
(P1)
63 mil ceramic
(a)
5 mil 20+ windings
tungsten (P2)
50 mil ceramic
Z1
Z2
P1
ISO122 amplifier
R
signal out
P2
Cx
(b)
±100V

Figure 2

(a)

(b)



measured
fit
probe current (a.u.)
0.4
0.2
0.0
5
10
15
probe voltage (V)
first derivative of probe signal
exponential fit
0.004
0.002
0.000
-10
0
10
20
probe voltage (V)

Figure 3

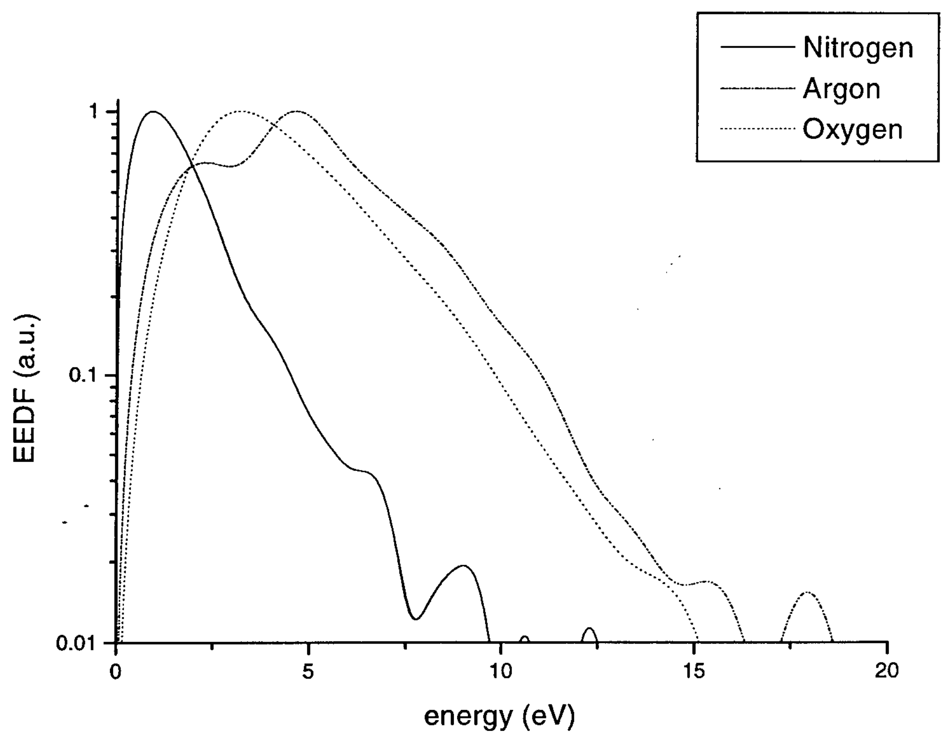


Figure 4

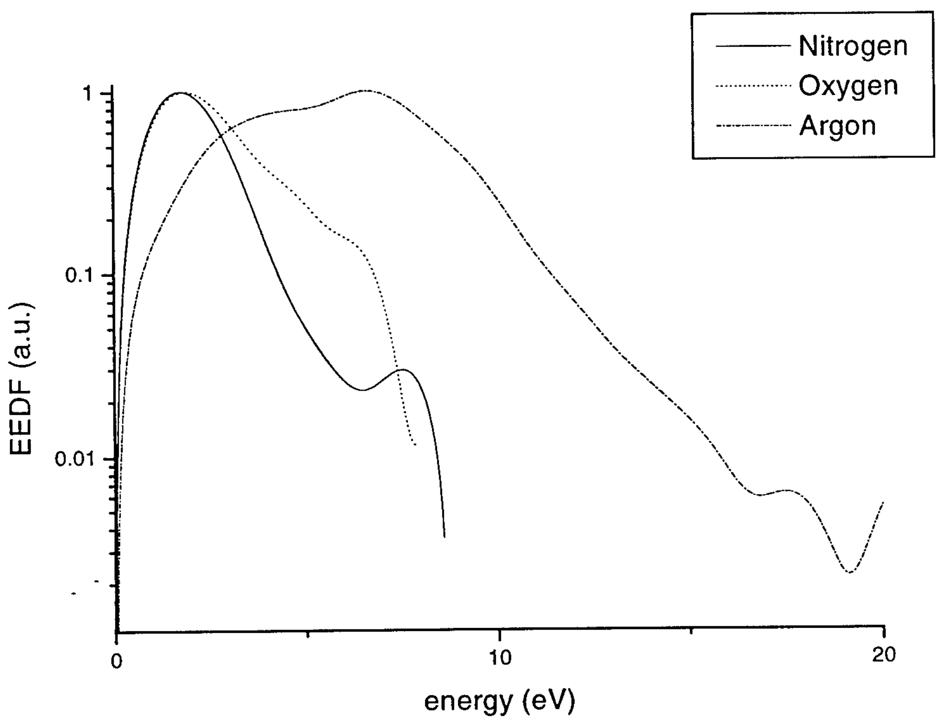
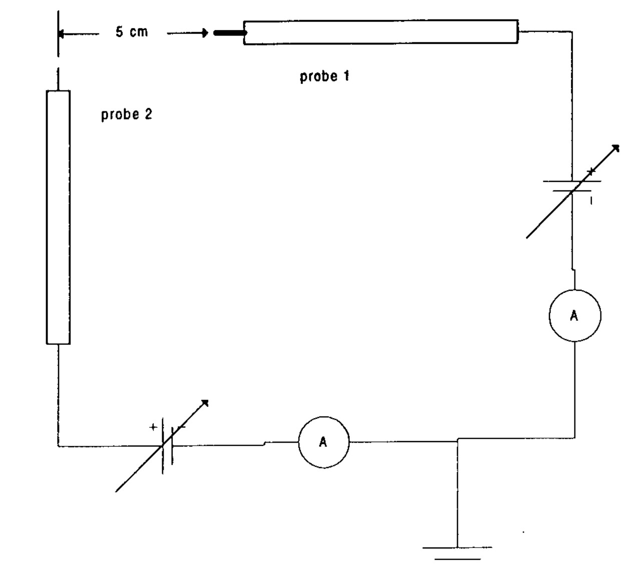


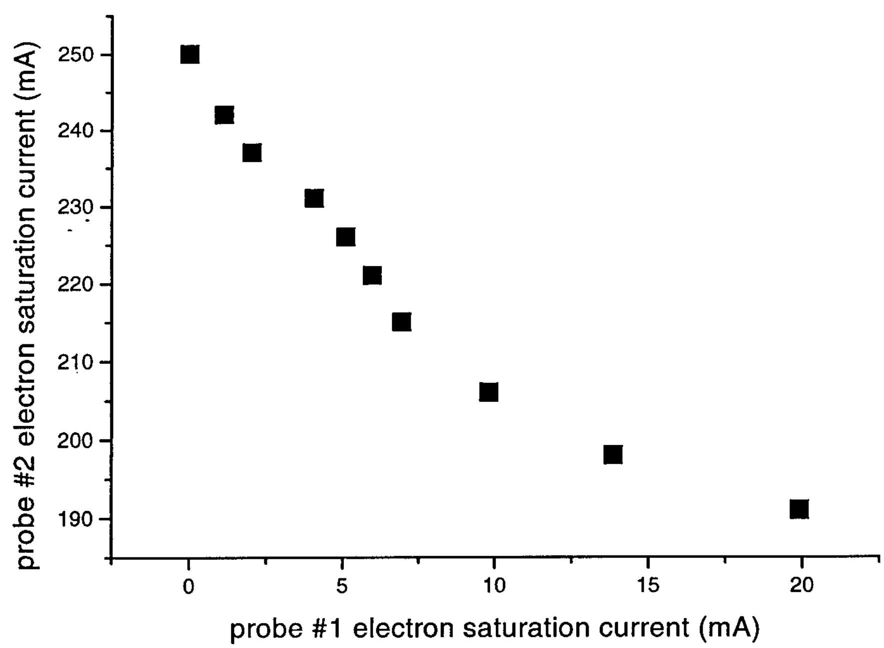
Figure 5

(a)



5 cm
probe 1
probe 2
A
A

(b)



probe #2 electron saturation current (mA)
250
240
230
220
210
200
190
0
5
10
15
20
probe #1 electron saturation current (mA)

Figure 6

	T_{eff} from Druyvesteyn method	T_e from Langmuir fit	T_e from exponential fit to first derivative
20 millitorr			
Ar	3.4	2.8	2.7
O2	2.8	2.7	2.8
N2	1.3	2.3	1.8
100 millitorr			
Ar	4.0	3.1	1.8
O2	1.8	1.5	2.1
N2	1.4	1.1	1.0

Table 1